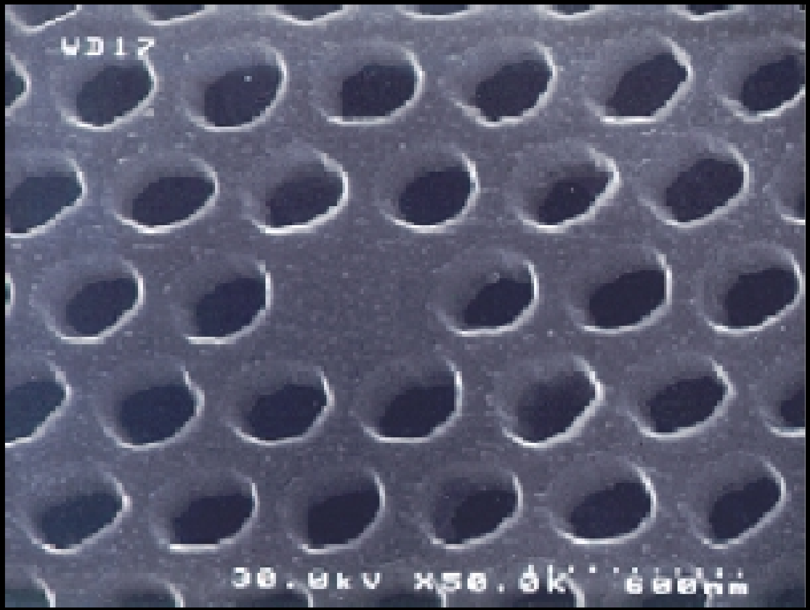
Photonic Crystal Devices

Axel Scherer
California Institute of Technology

Research Opportunity:

- To construct compact, robust, monolithic and multi-functional nano-photonic integrated circuits.



Report Documentation Page	*Form Approved OMB No. 0704-0188*			
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1. REPORT DATE **18 APR 2000**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**		
4. TITLE AND SUBTITLE **Photonic Crystal Devices**		5a. CONTRACT NUMBER		
		5b. GRANT NUMBER		
		5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)		5d. PROJECT NUMBER		
		5e. TASK NUMBER		
		5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **California Institute of Technology**		8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)		
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**				
13. SUPPLEMENTARY NOTES **DARPA/MTO, WDM for Military Platforms Workshop held in McLean, VA on April 18-19, 2000, The original document contains color images.**				
14. ABSTRACT				
15. SUBJECT TERMS				
16. SECURITY CLASSIFICATION OF: a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	17. LIMITATION OF ABSTRACT **UU**	18. NUMBER OF PAGES **25**	19a. NAME OF RESPONSIBLE PERSON

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Collaborators on Photonic Crystal Devices: Design, Fabrication and Measurements

• Dan Dapkus	*U.S.C.*	*InGaAsP growth*
• Tom Pearsall	*Corning*	*Waveguides*
• Amnon Yariv	*Caltech*	*Device Integration*
• Dennis Deppe	*U. Texas*	*Quantum Dots*
• Eli Yablonovitch	*UCLA*	*PBG design*

Goal: To develop photonic crystal devices and connect them together to form compact integrated WDM systems.

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Planar Photonic Crystals in Chip-Scale WDM

⇒ Dense arrays of optical elements can be lithographically coupled together.

⇒ Low threshold lasers with ultra-small mode volumes can be constructed and tuned.

⇒ Photonic integrated circuits can be constructed with sources, modulators, filters and detectors.

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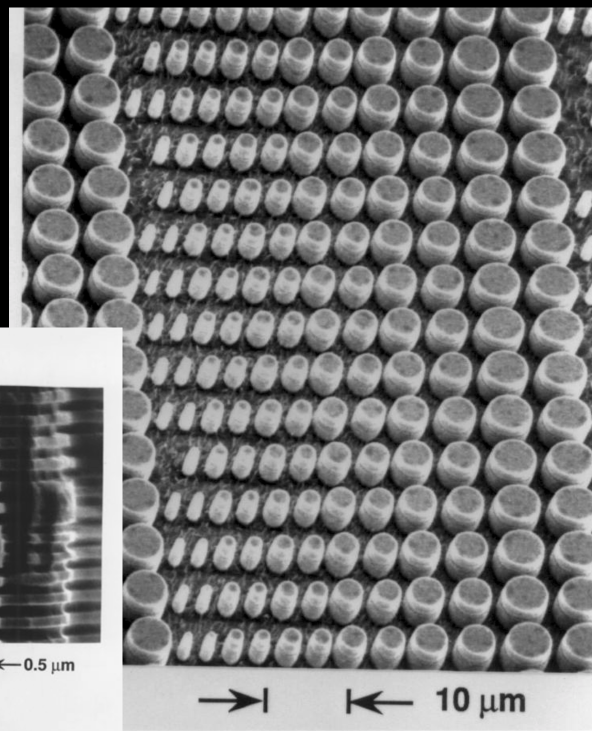
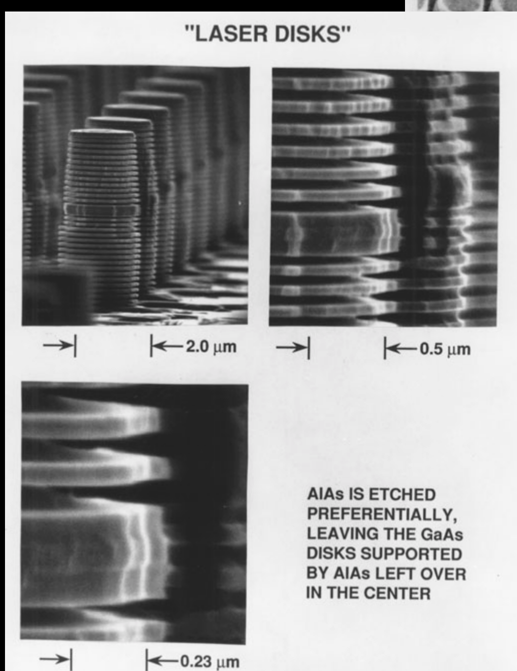
Vertical Cavity Surface Emitting Lasers (1989)





- Mirrors and active area are controlled by crystal growth
- Light emits perpendicular to the wafer surface
- Threshold currents as low as 10 µA have been reported
- VCSELs are presently used for fast optical interconnects

J.L. Jewell, A. Scherer, S. McCall, J. Harbison

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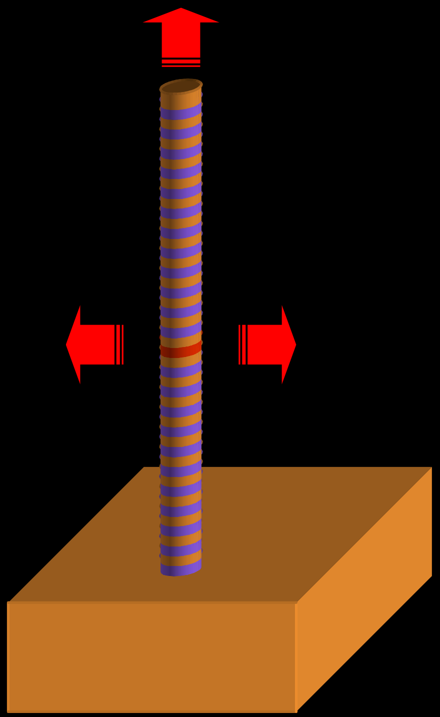
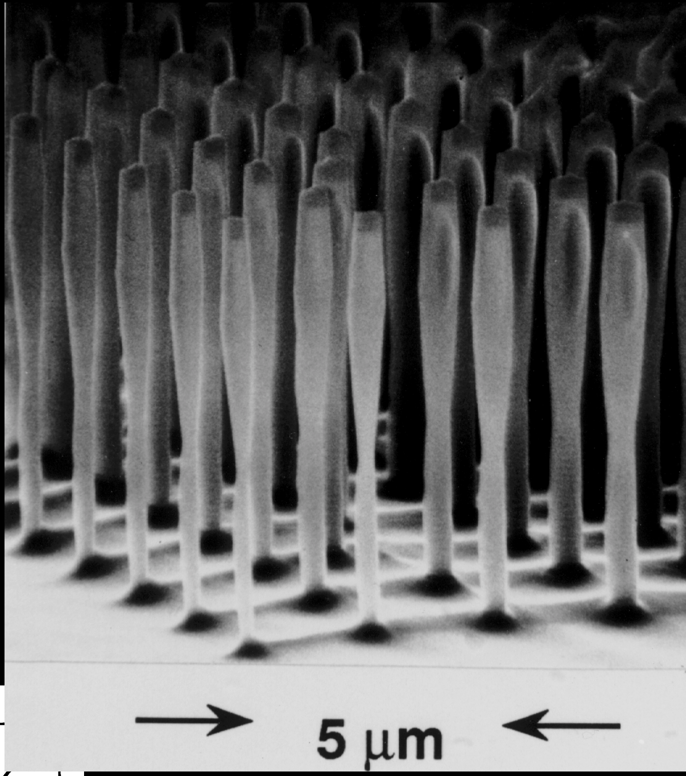
Ultra-small vertical cavity lasers



The mode volume of VCSELs could be reduced to one cubic wavelength



Jewell, Scherer, Harbison, (1991)

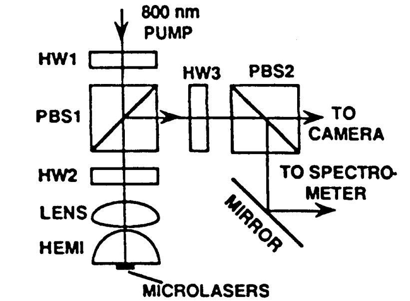


Fig. 4. Schematic of the experimental setup.

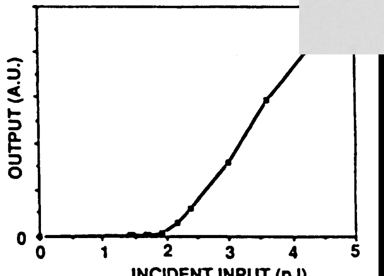
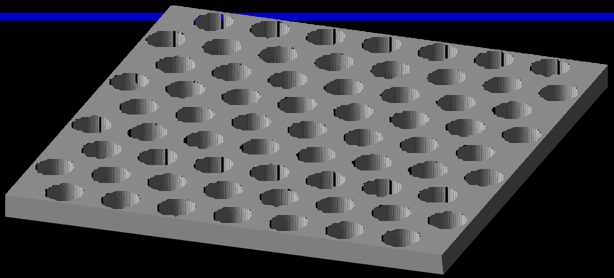
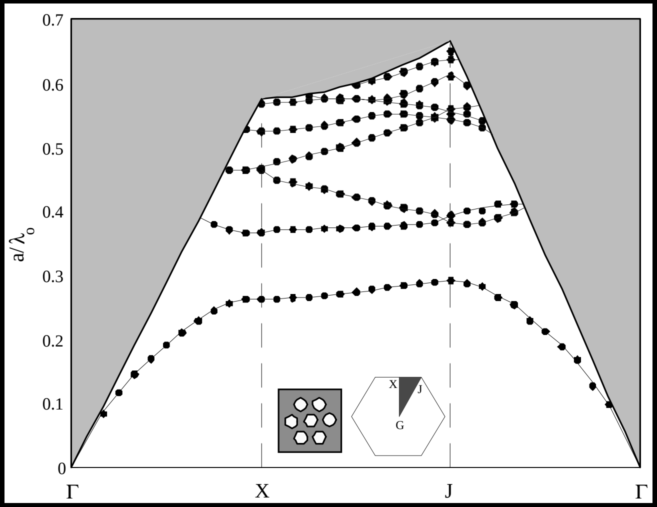


Fig. 5. Output at 865 nm vs. incident input energy for a 0.4X0.4 μm microlaser.

2D Photonic Crystal Waveguide



- TIR provides vertical guiding in an optically thin slab as in the microdisk.
- High index contrast periodic dielectric lattice provides strong dispersion ➡ photonic bandgap.



Note: 2-D photonic crystals were first proposed by Joannopolous et al. at MIT

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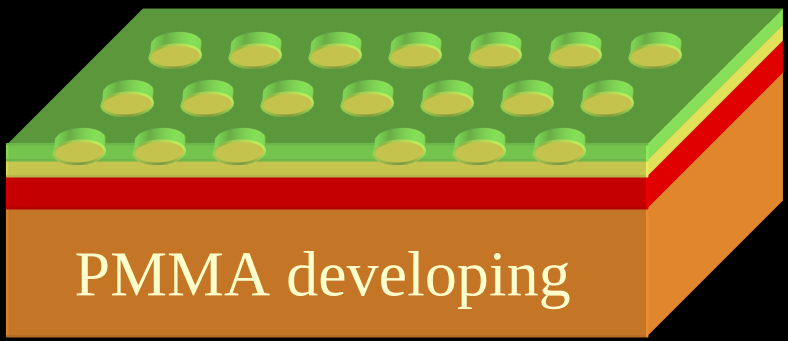
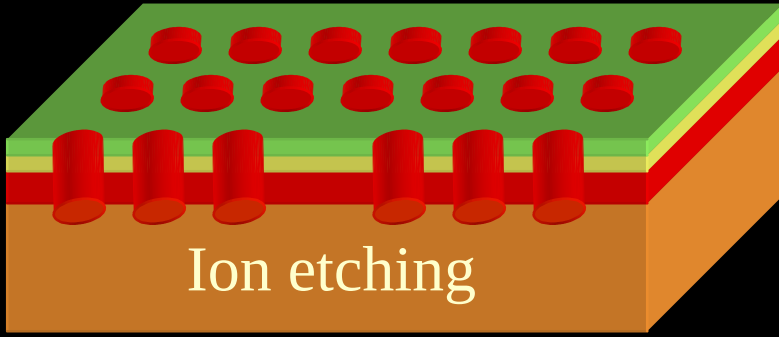
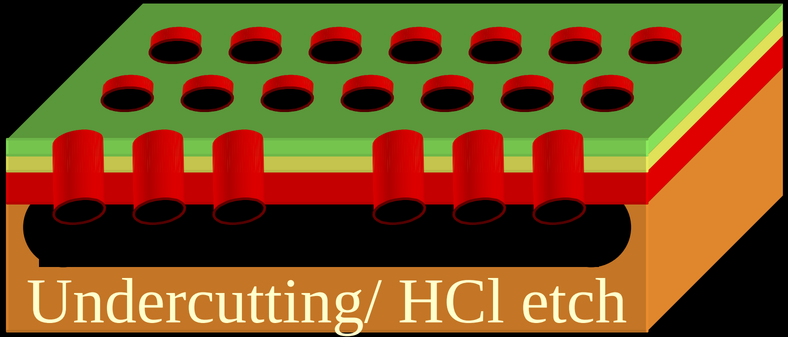
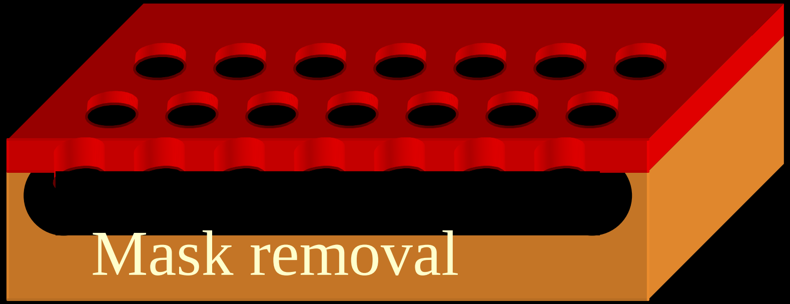
Fabrication Sequence

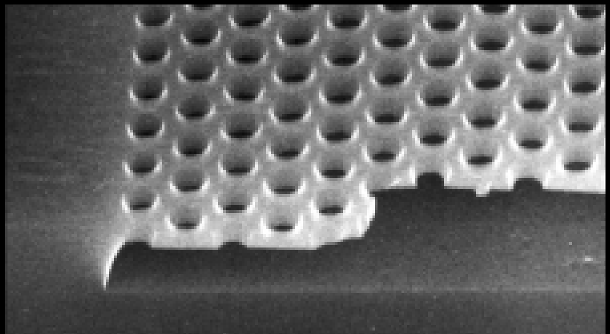
Photonic Crystal membranes are constructed by lithography, ion etching, and chemical etching











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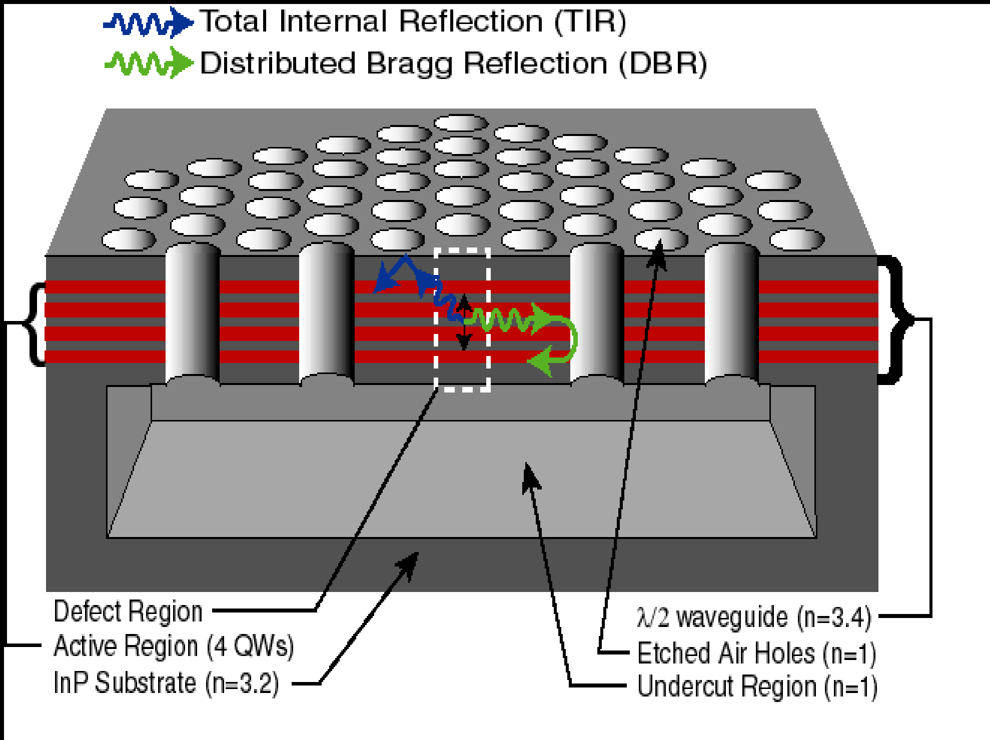
Photonic Crystal Laser Schematic



- The defect cavity localizes light through total internal reflection at the air/slab interface and Bragg reflection from the 2D photonic crystal.
- The high-index slab (n=3.4) contains 4 QWs for gain, and is only 200 nm in thickness.

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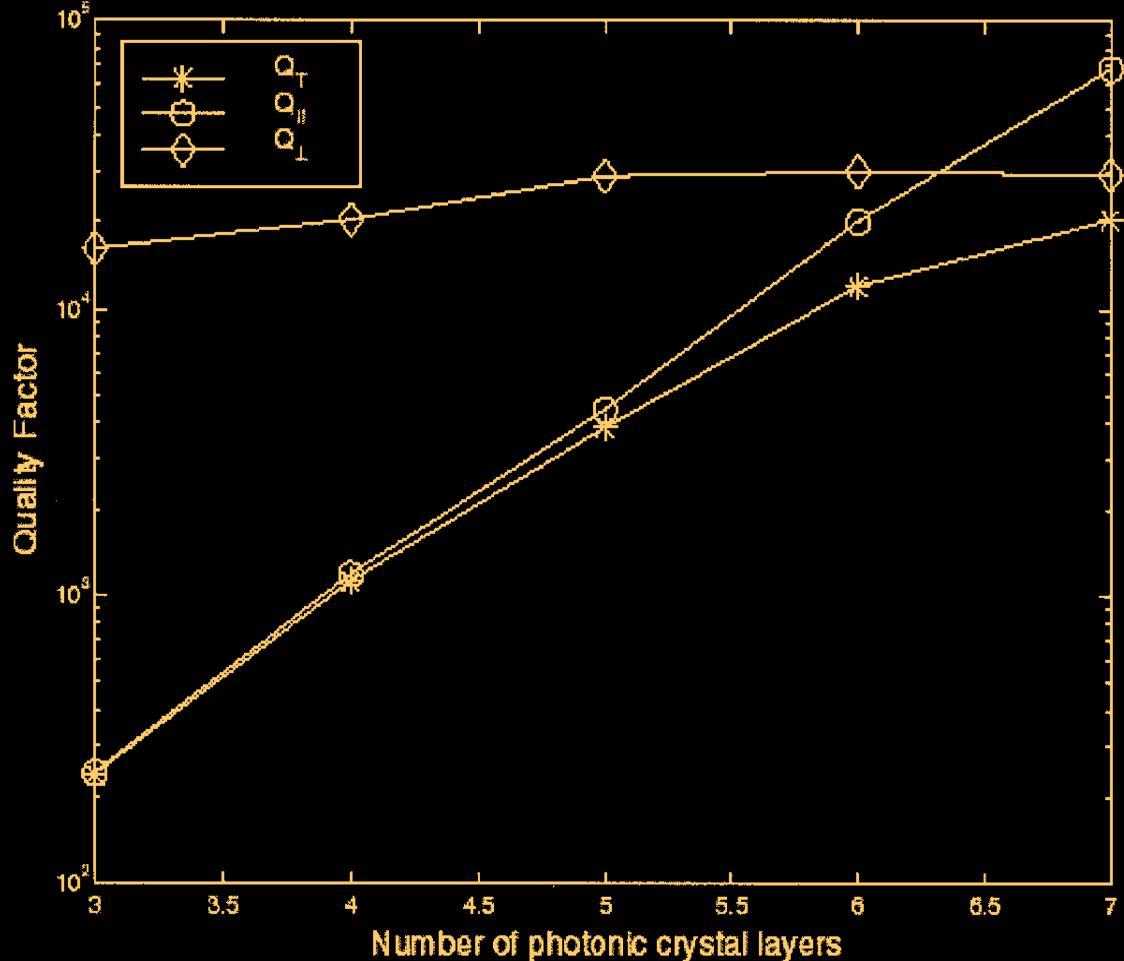
Q dependence on number of PBG layers

$$\frac{1}{Q_T} = \left(\frac{1}{Q_\perp} + \frac{1}{Q_{//}}\right)$$



Single defect photonic crystal cavities can be useful high Q (>20,000) resonators.

Qs of 2-D Fabry-Perot resonators increase with number of PBG layers.

High quality cavities with 0.03 cubic micron volumes can be defined.

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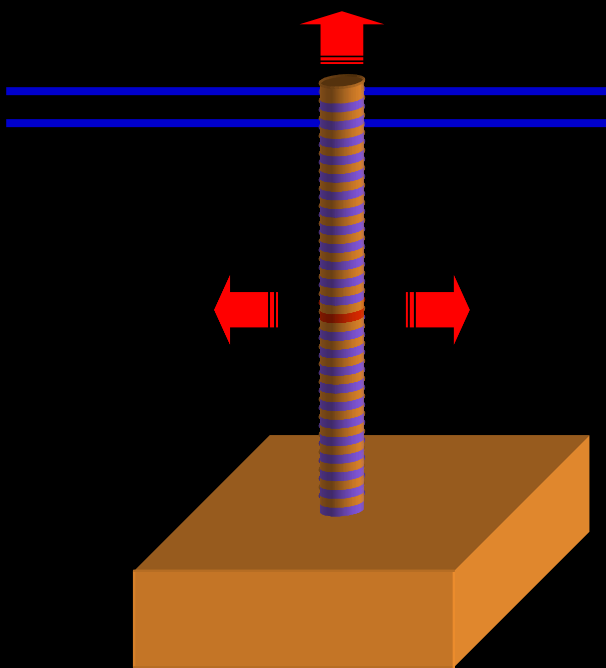
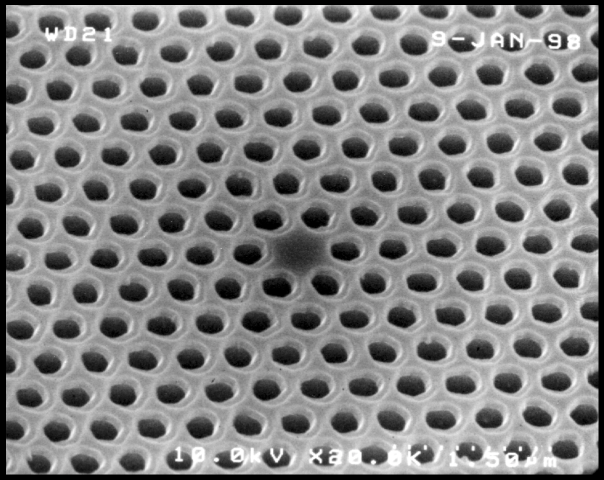
VCSELs and Photonic Crystal Lasers



- Mirrors are defined by growth
- The cavity can support many lasing modes
- Devices are difficult to couple together

- Mirrors are defined by lithography and etching.
- Only one or two lasing modes are supported in the cavity.
- Lasers can easily be coupled together in-plane.



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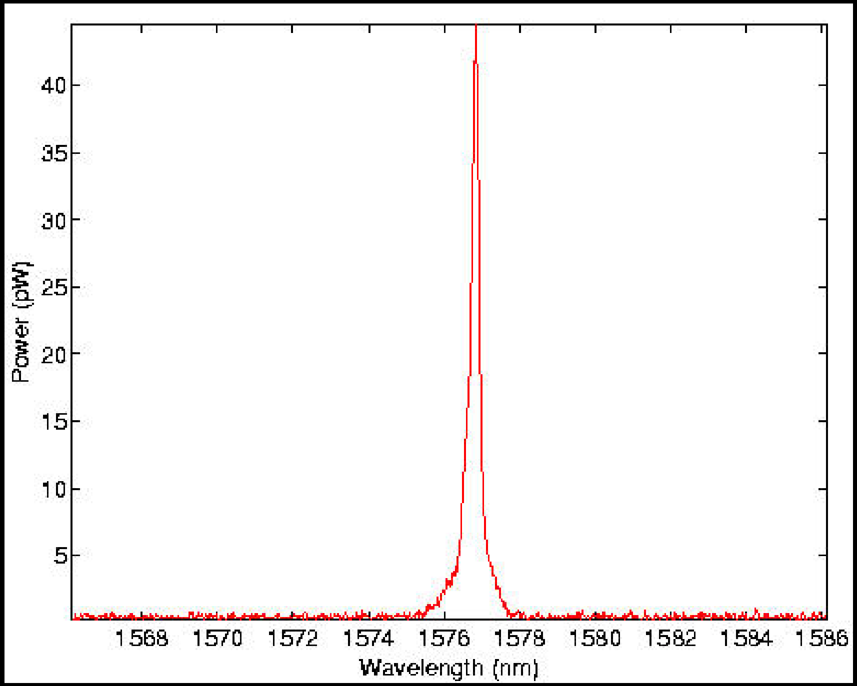
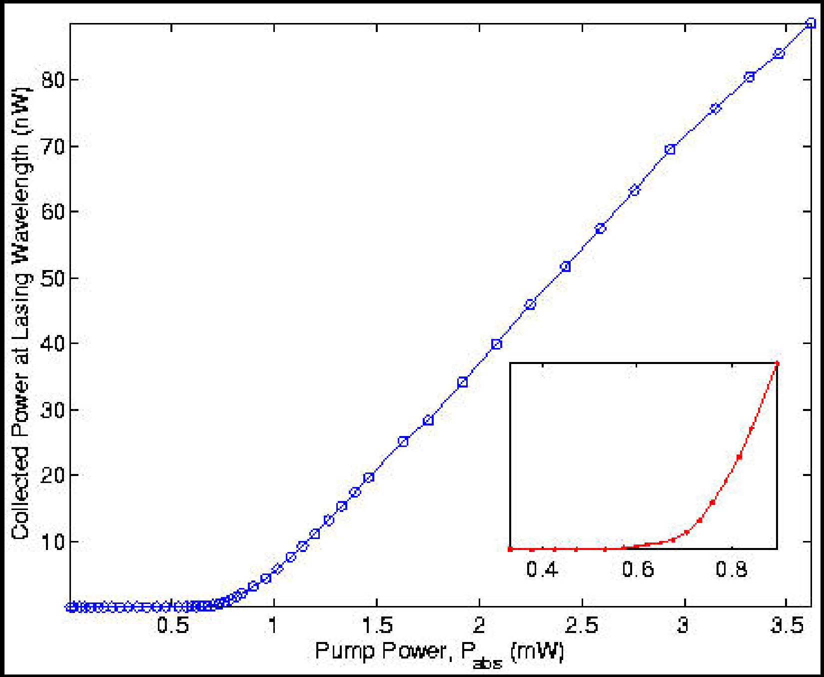
Room Temperature Lasing



Laser Spectrum of single defect

L-L curve of PBG laser



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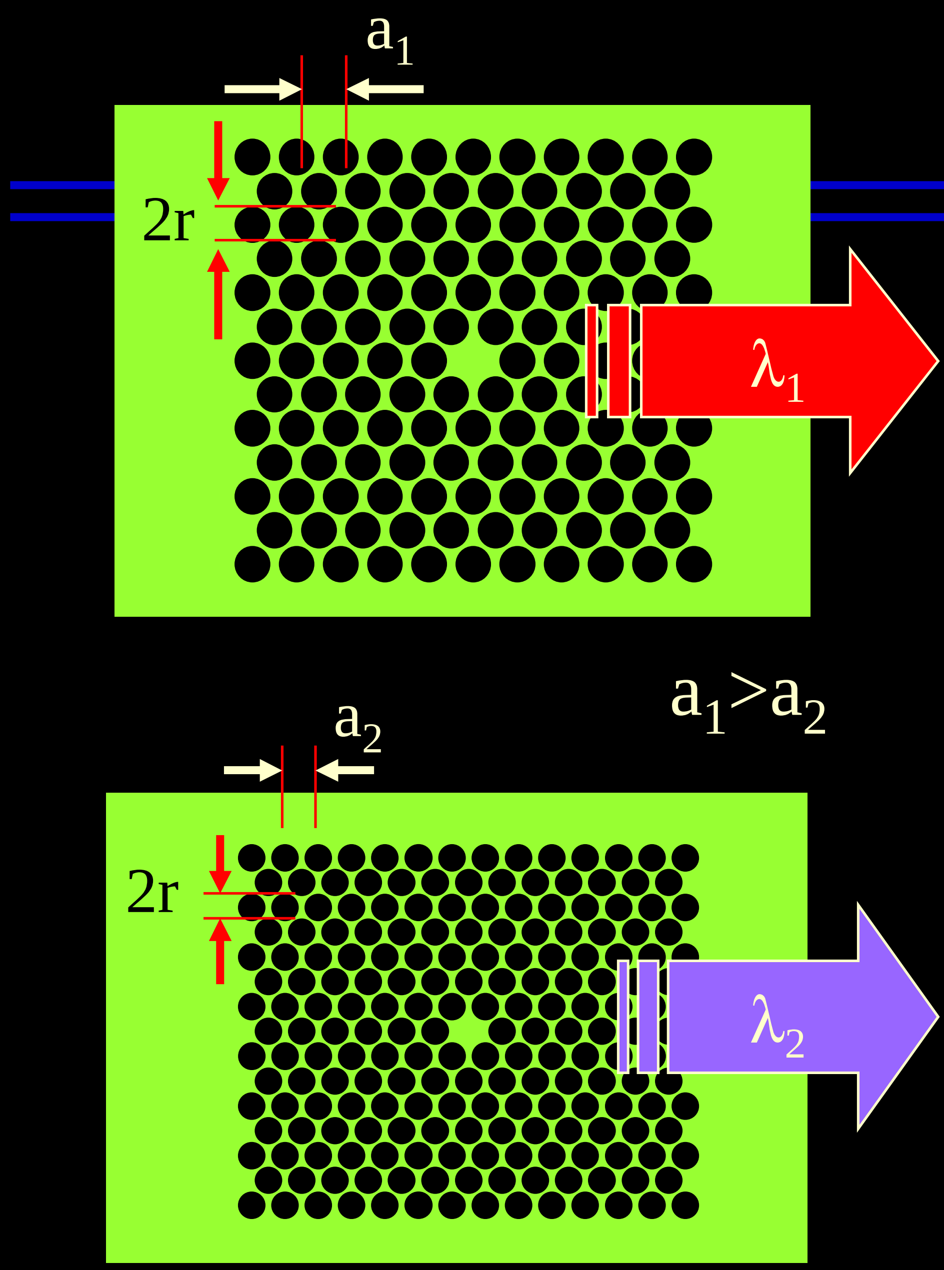
Tuning of Photonic Crystal Lasers



- The distances between holes determine the wavelength of emission from photonic crystal lasers.
- Multi-wavelength laser arrays can easily be constructed.

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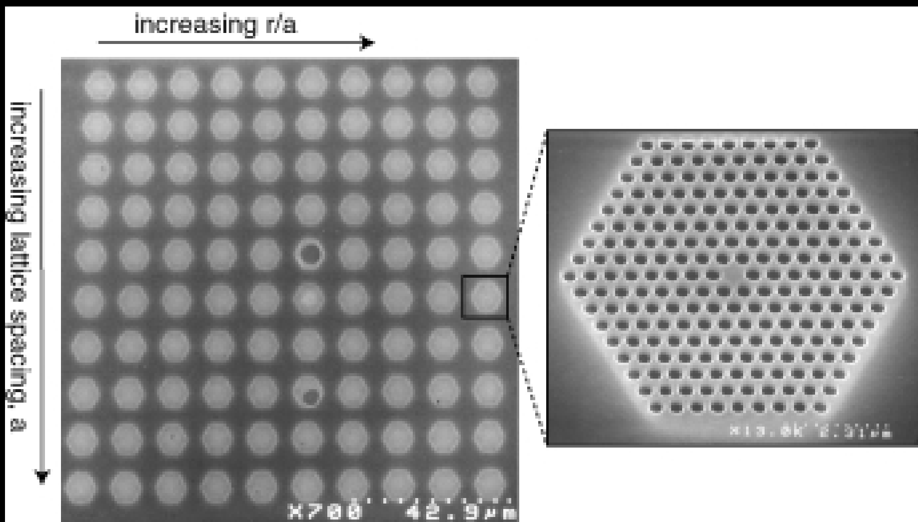
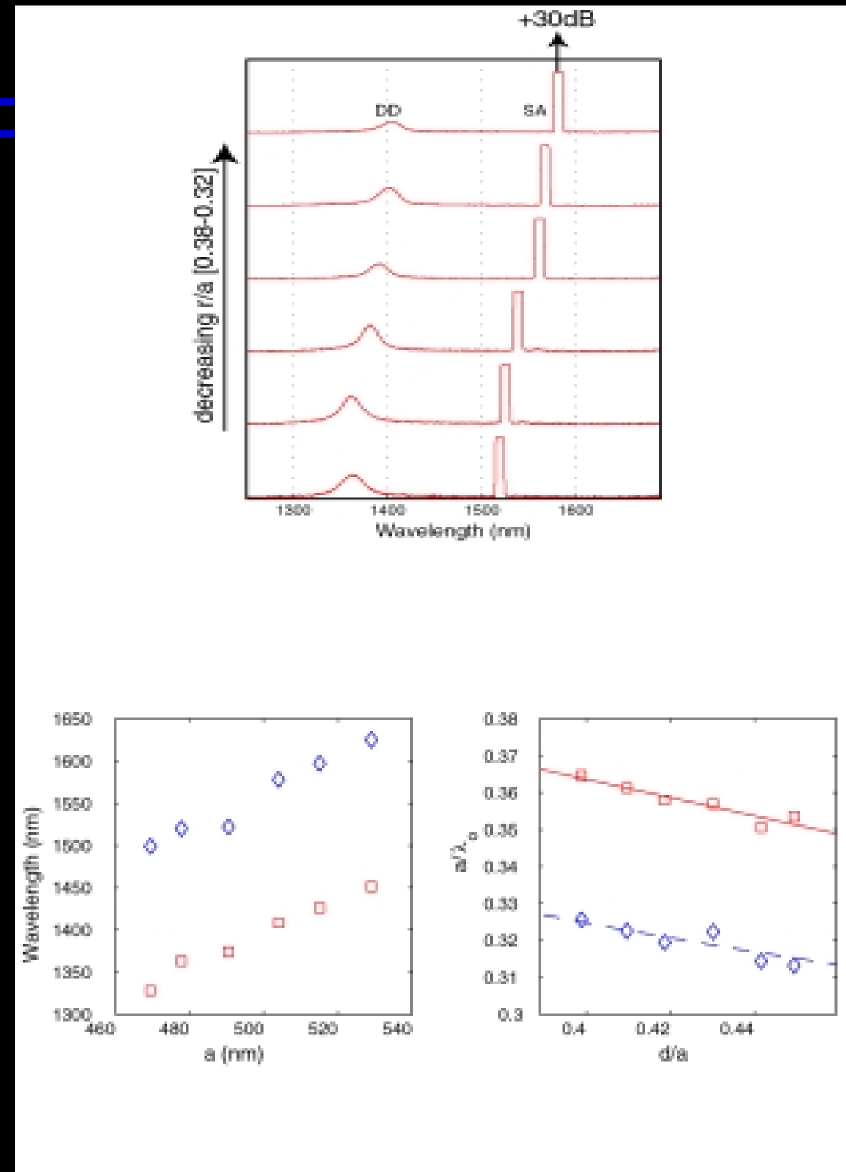
Multi-Wavelength Laser Array





- Wavelength tuning from 1500 - 1620 nm.
- Wavelength resolution of 10 nm [limited by fabrication tolerances].

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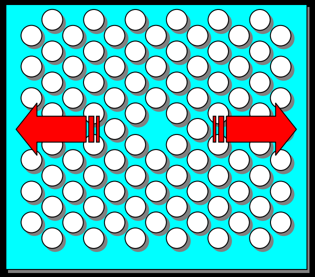
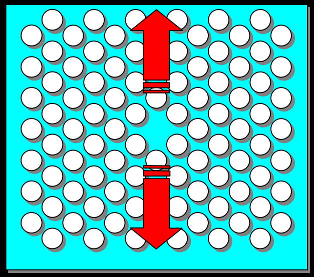
Controlling the direction of laser emission



X dipole



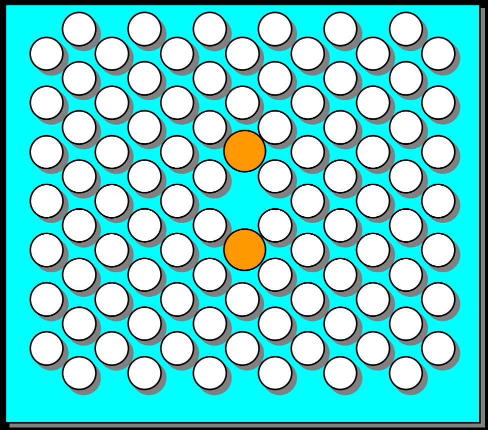
Y dipole

To control the direction and polarisation of the laser emission, we can:

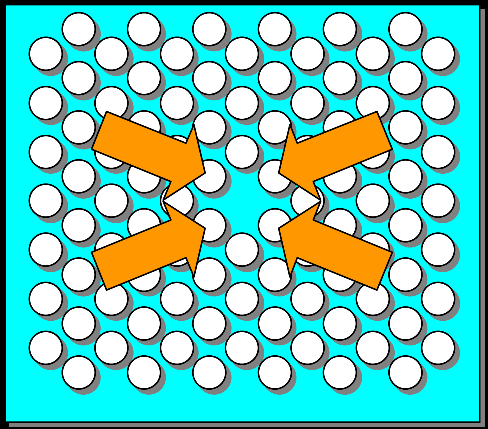
(a) increase the radius of some of the holes next to the cavity, or

(b) move some of the holes closer or further away from the cavity.

a



b



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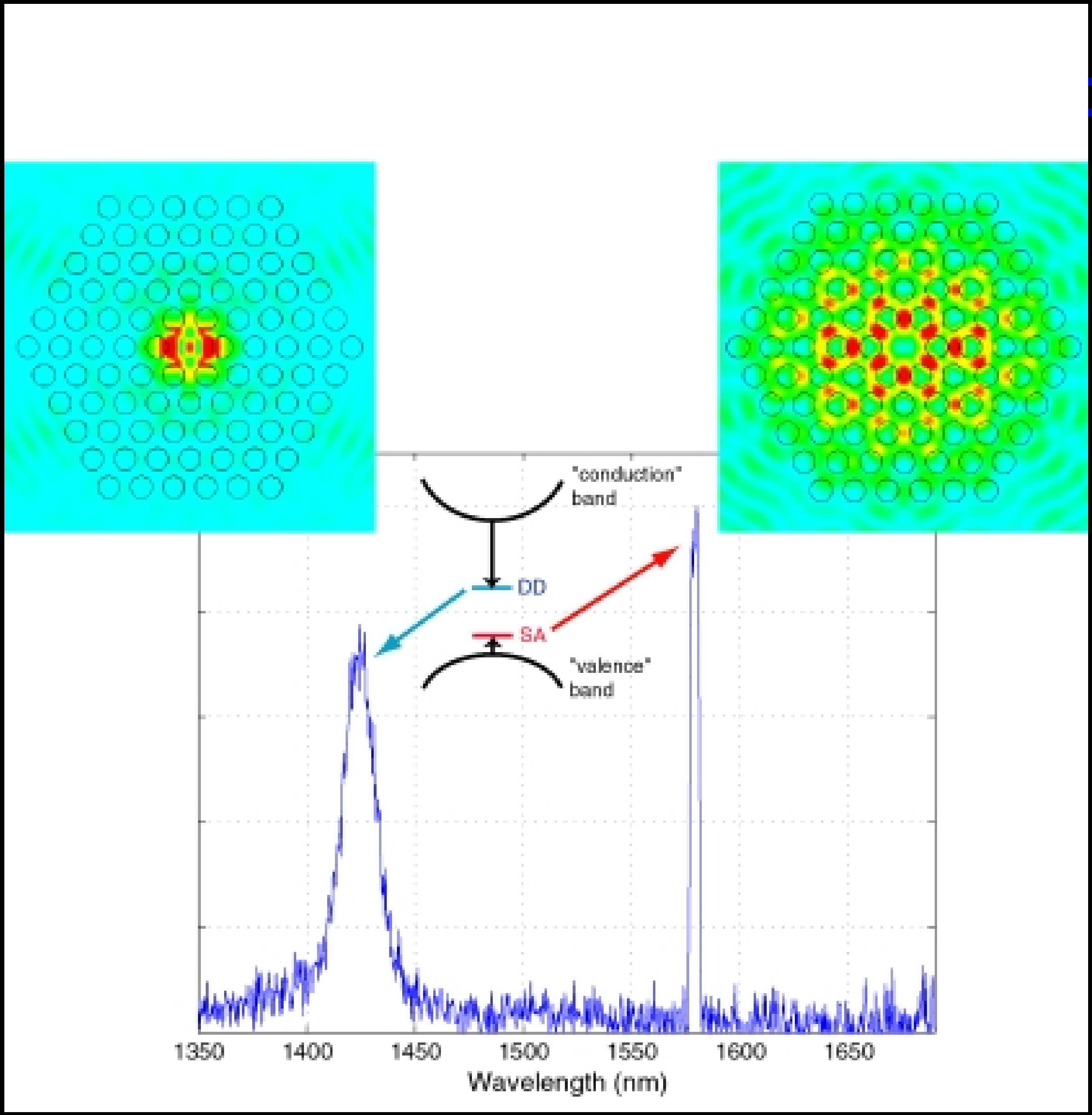
Near-Threshold Spectra



Both deep donor and shallow acceptor modes can be supported by the same cavity

These modes can also be identified in the luminescence spectra

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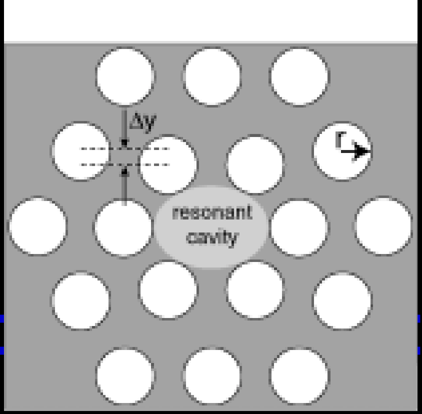
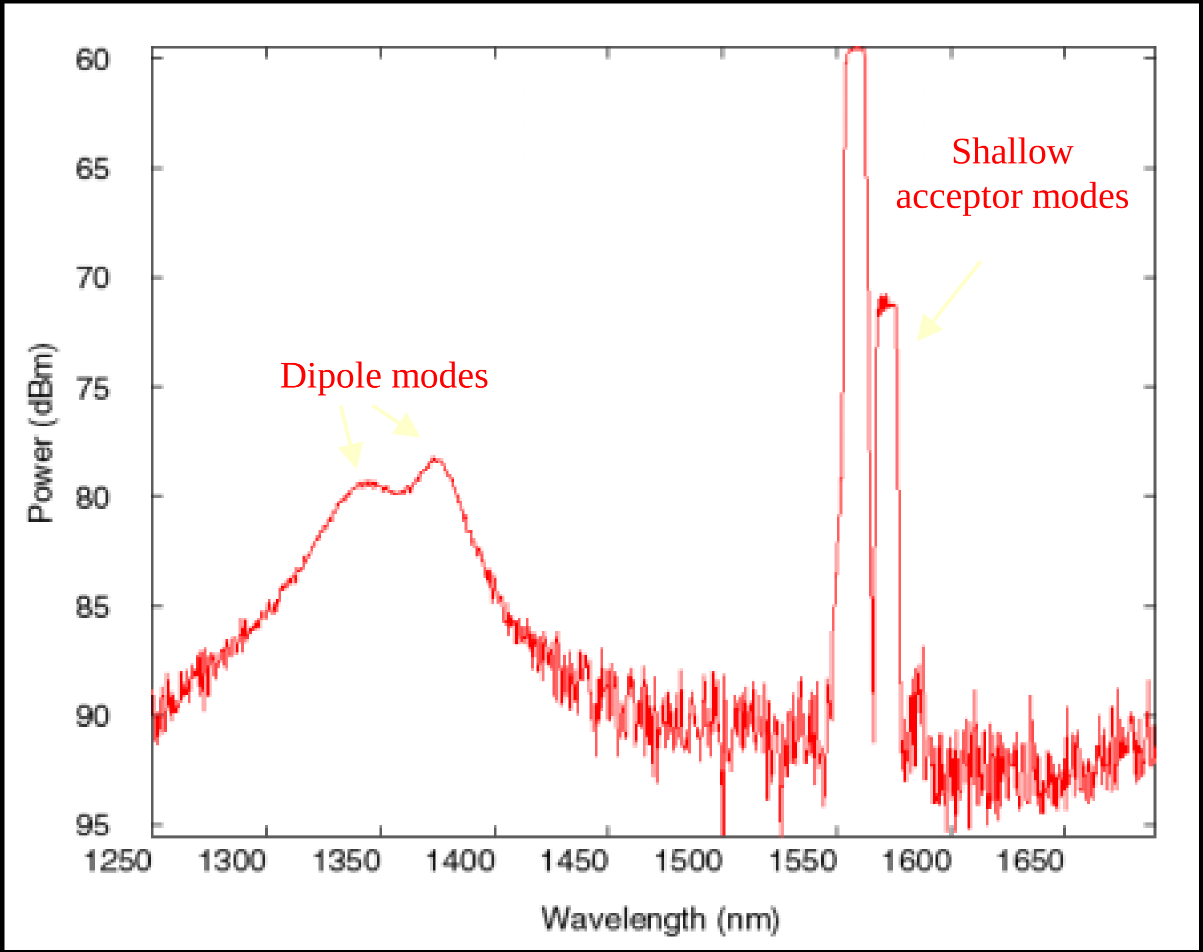
Split-2 Spectra





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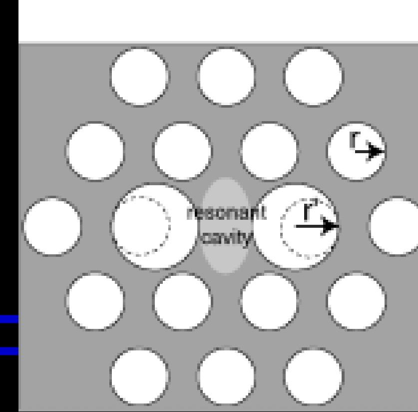
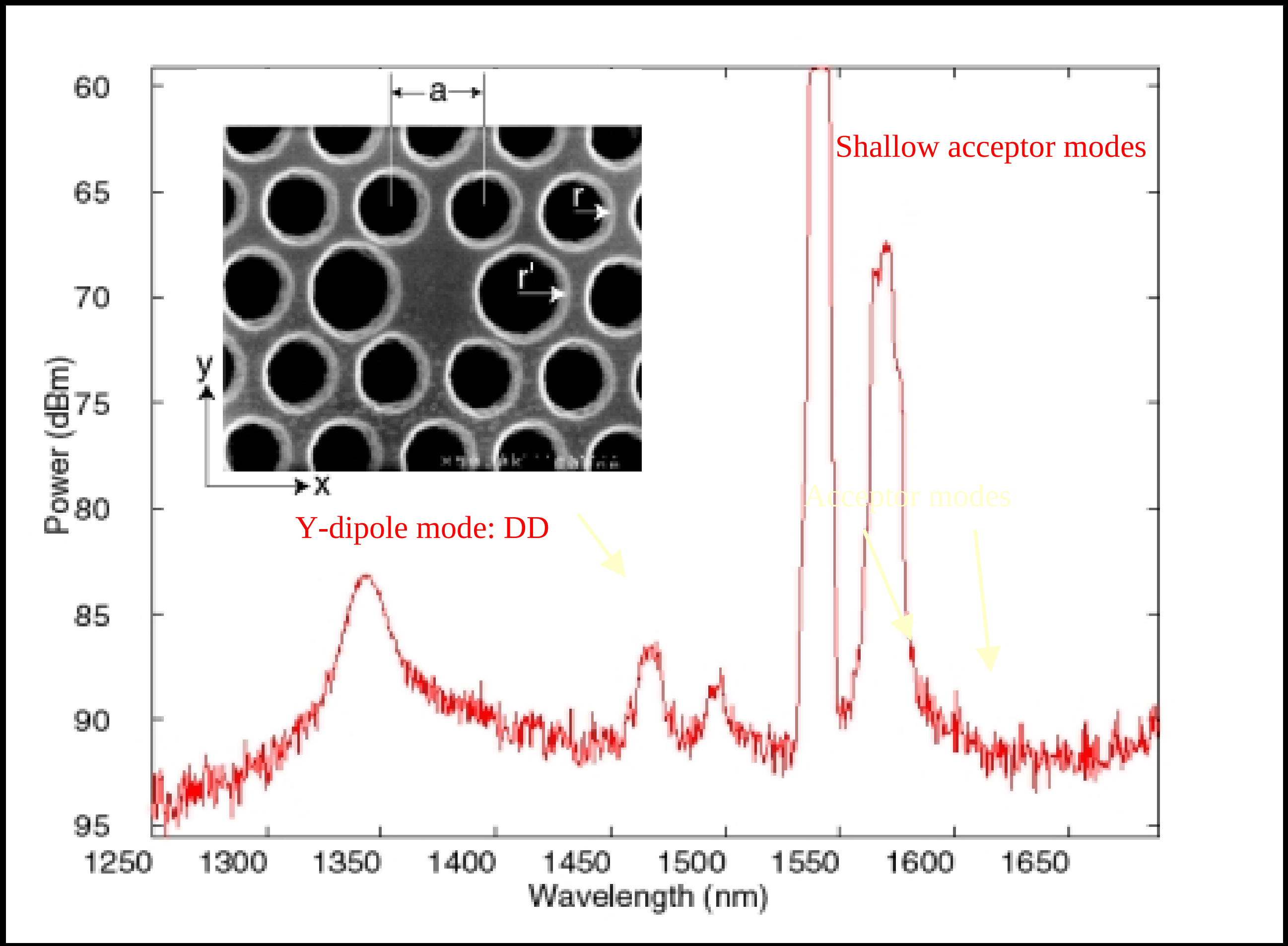
Split-1 Spectra





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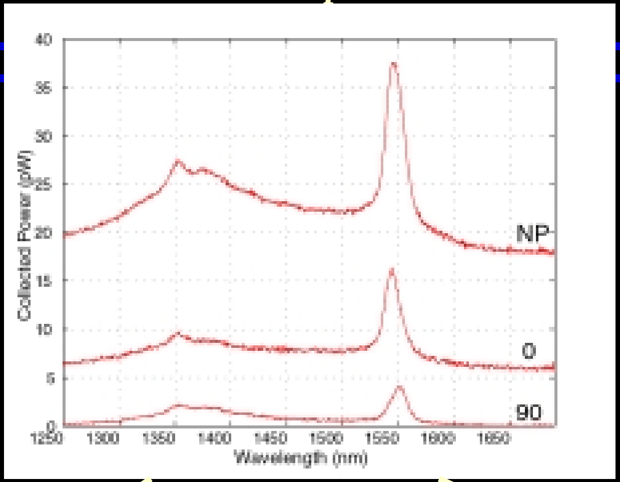
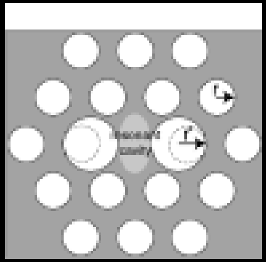
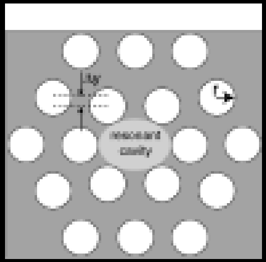
Polarization Measurements

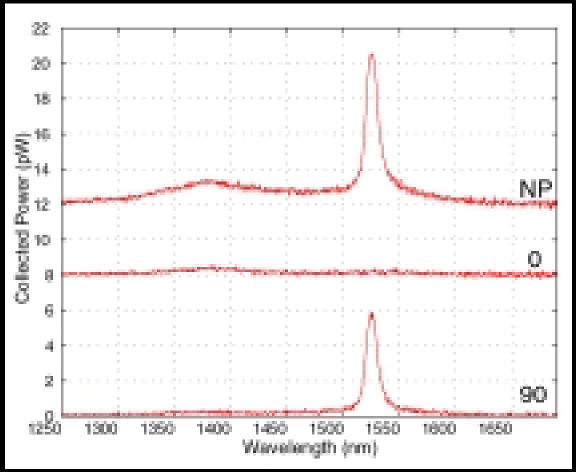
Un-Split



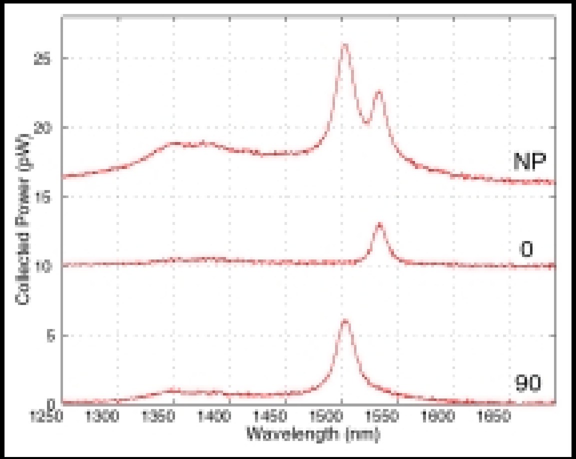




Split-1



Split-2



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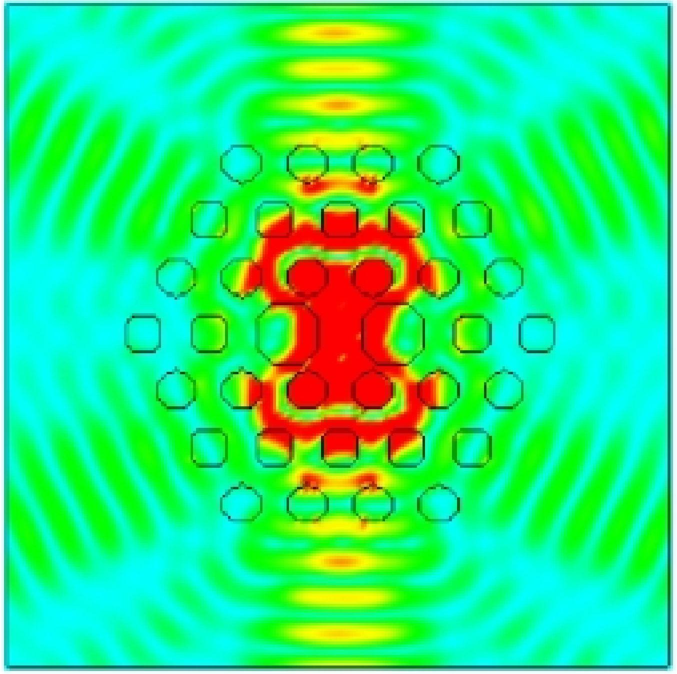
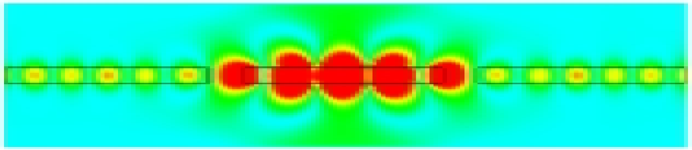
Emission Pattern from Optimized Cavity

- Defect mode can be controlled through lithography to radiate vertically or in-plane.
- Two enlarged holes concentrate the in-plane emission along one-axis.



In-Plane emission (FDTD simulation)



Vertical Emission (cut through slab)

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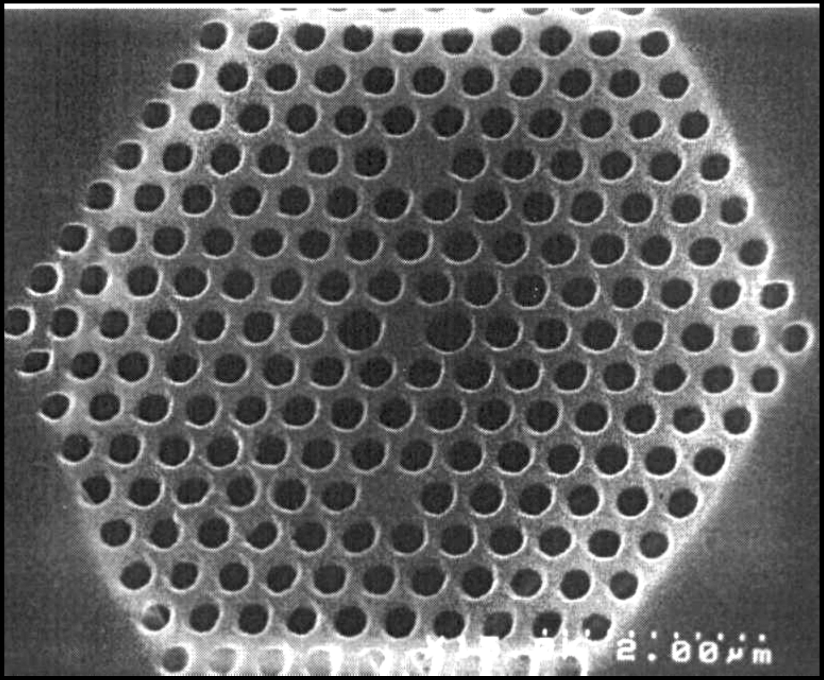
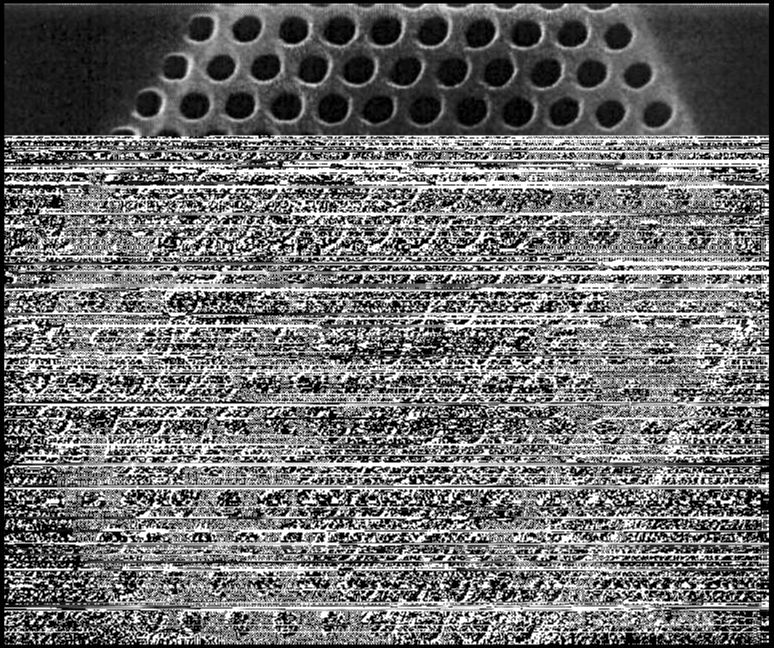
Lithographically connected optical cavities

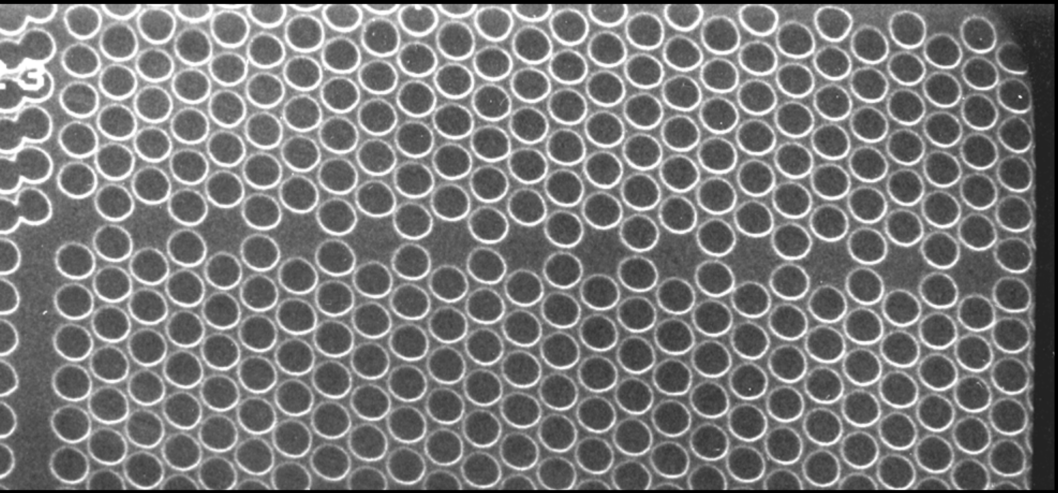


Several cavities can be connected lithographically to form routers and switches



Diffraction losses can be minimized by using photonic crystal mirrors between devices

Coupled Resonant Optical Waveguides



- Waveguides can be constructed to change the phase velocity of light.

Applications may include:
- optical traveling wave tubes
- higher harmonic light generation
- pulse reshaping

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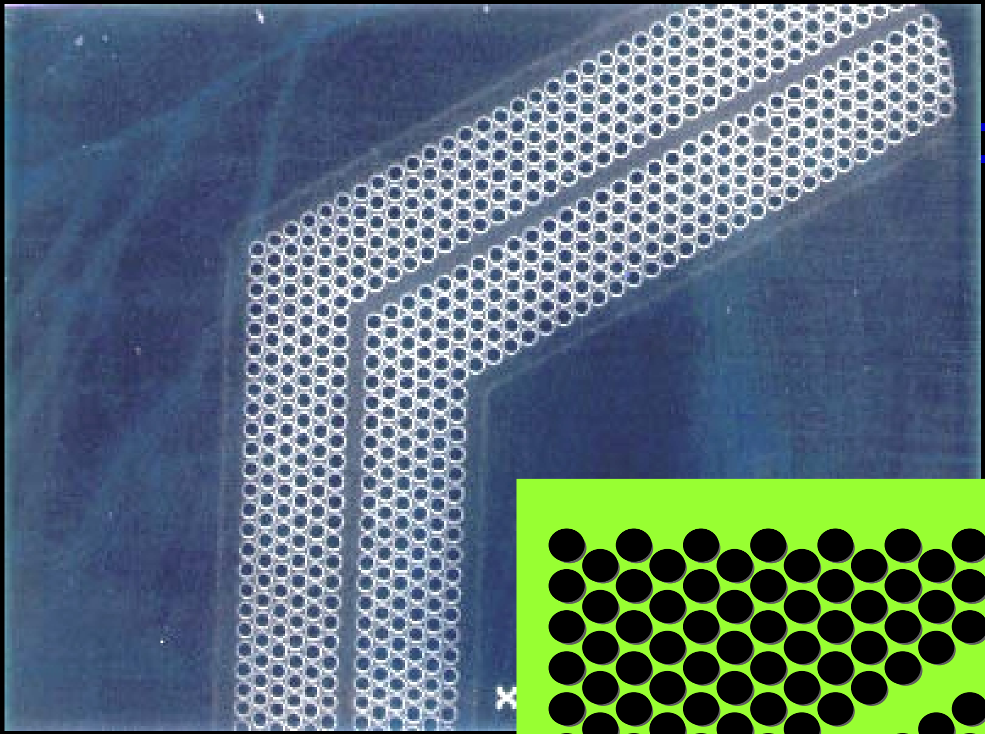
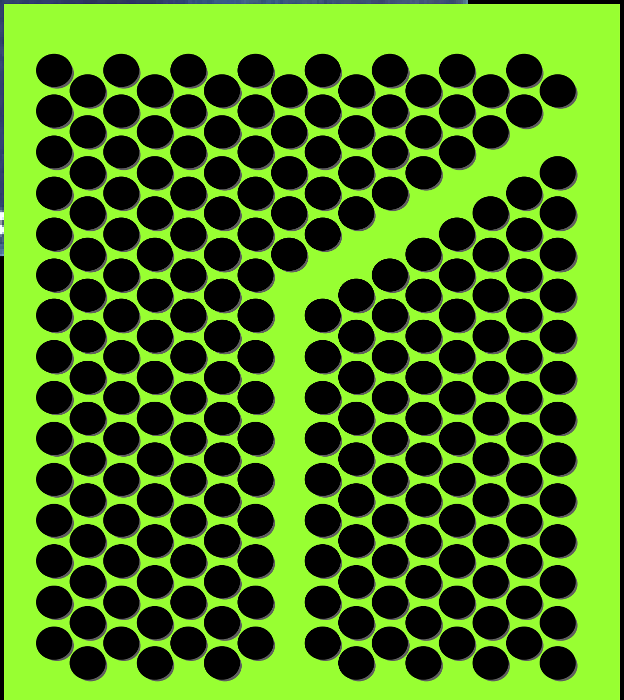
Waveguides in Photonic Crystals





A photonic crystal waveguide can be defined by eliminating lines of holes from the photonic crystal.

This waveguide can be used to connect lasers, detectors and filters.

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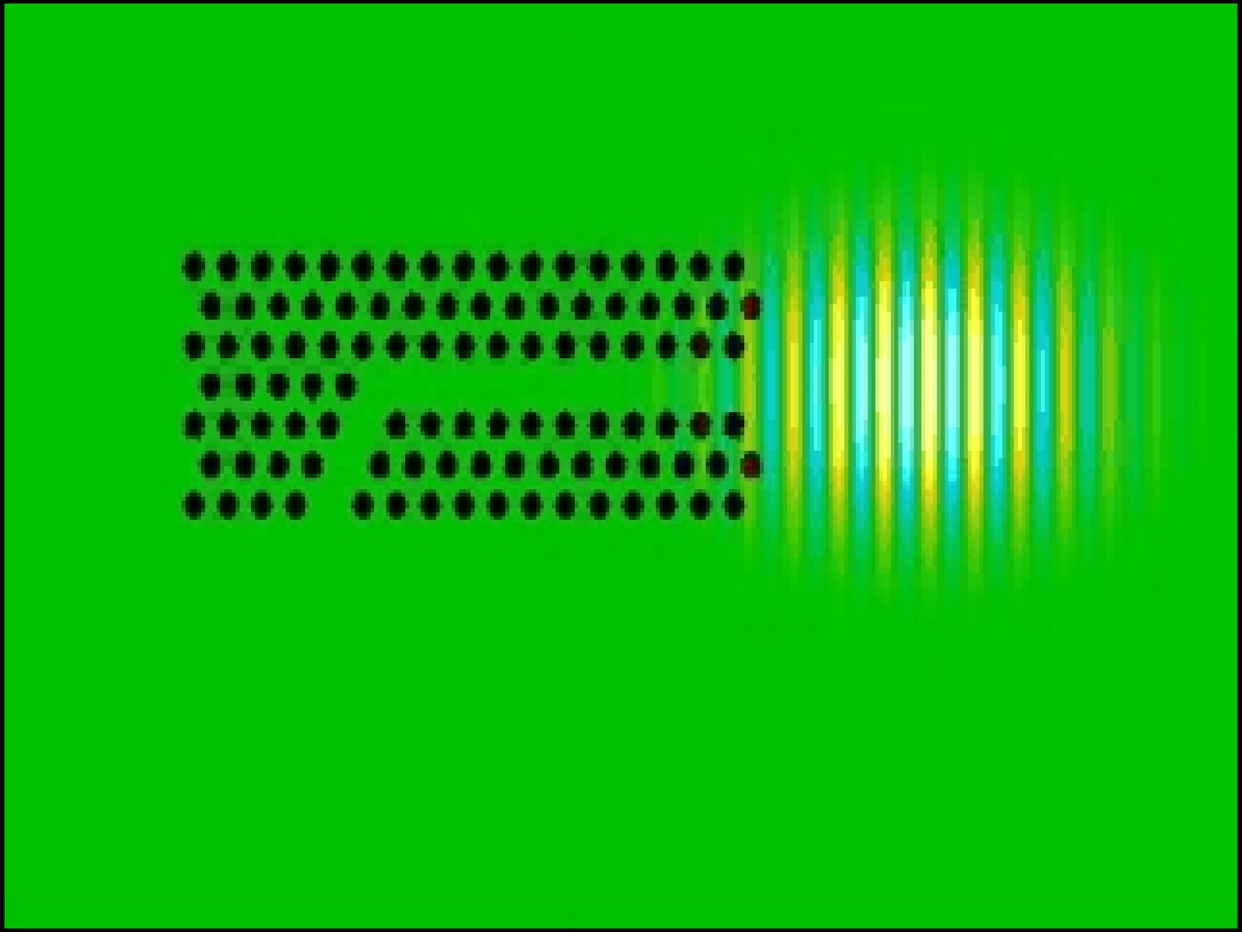
Guided Light in a PBG Waveguide (FDTD model)



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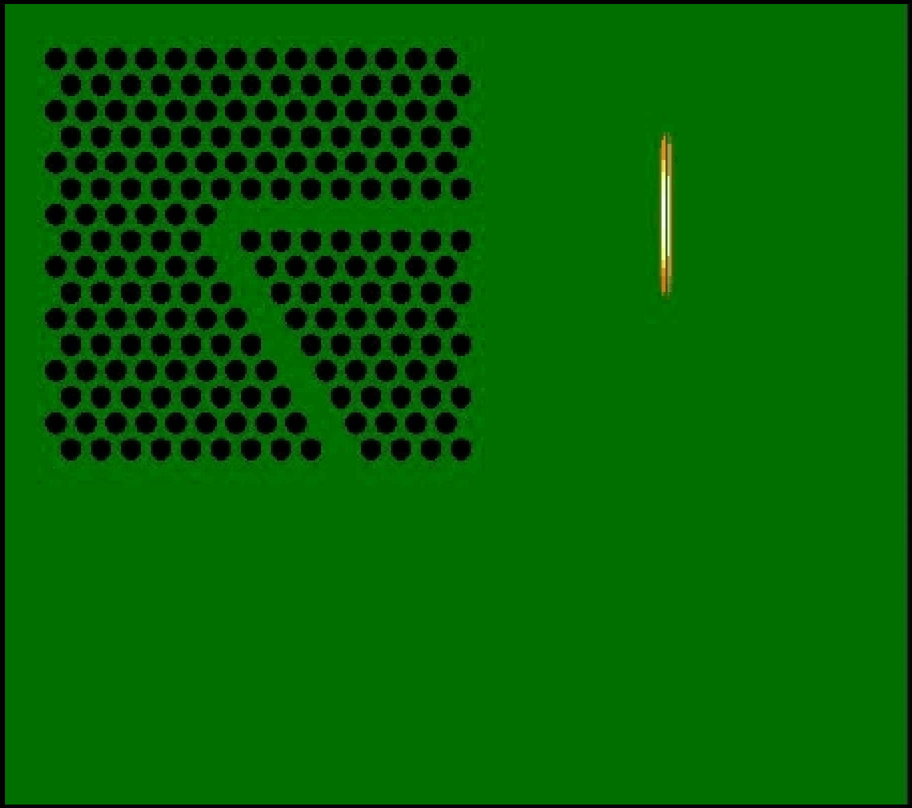
Finite Difference Time Domain Calculation of 120^o Bend



Bend geometries can be designed in both 2-D and 3-D by using FDTD programs distributed on a multi-computer cluster.

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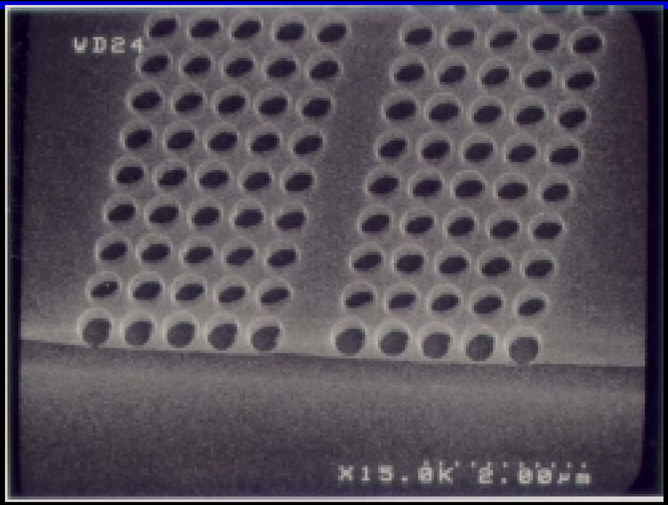
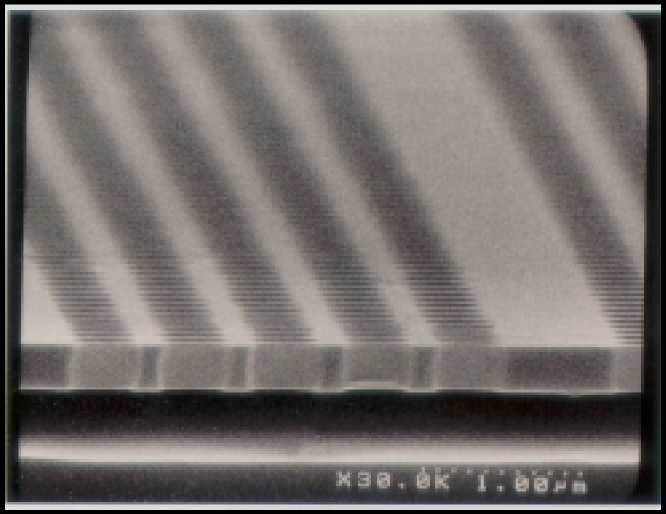
Si Photonic Crystal Waveguides





- Silicon on Insulator (SOI) allows the easy fabrication of single mode optical wave-guides for 1.55 μm
- Photonic crystal mirrors can be used to construct very sharp waveguide bends with low losses.